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A continuous-time closed-loop interface with an innovative C/V converter for gyroscopes

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Abstract

A continuous-time (CT) bandpass sigma-delta modulation based closed-loop interface implemented with an innovative charge-to-voltage (C/V) converter is proposed in this paper. Compared to conventional CT closed-loop implementations with large feedback resistors to settle the input common mode (CM) voltage of the amplifier within the C/V converter, the proposed C/V converter with reset is simple and has an area advantage. Additionally, it contributes adequate phase shift to eliminate the compensator which is necessary in a closed loop, thus further reducing the area, as well as power consumption.

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1. Introduction

Micromachined inertial gyroscopes are widely used either as a low-cost miniature companion with micromachined accelerometers to provide heading information for inertial navigation purposes or in other areas, including automotive applications for ride stabilization and rollover detection; further consumer electronic applications, such as video-camera stabilization, virtual reality, and inertial mouse for computers; robotics applications [1]. A gyroscope generally consists of two main parts, i.e., a mechanical sensor and an electrical interface. The detected angular rate is modulated by the drive mode of the sensor to generate a Coriolis force F_{coriolis} .

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The F_{coriolis} is processed by the sense mode of the sensor, yielding a varying capacitance ΔC which is proportional to the detected angular rate modulated by the drive signal. The C/V converter translates ΔC to the output voltage of the C/V converter which is further processed by the interface to gain an overall output V_{output} representing the magnitude of the detected angular rate. There are many different configurations of interfaces for gyroscopes. A fourth-order sigma-delta interface for inertial sensors was proposed in [2] implemented as switched capacitor circuit. In [3], both lowpass and bandpass high-order sigma-delta modulator topologies were derived at system level, and it was found that the bandpass topology had distinct advantages over the lowpass topology. An interface based on bandpass sigma-delta modulators in CT topology was presented in [4]. There are also open loop configurations without stability issues [5].

In this work, the proposed C/V converter takes advantage of a reset to settle the input CM of the amplifier within the C/V converter. A CT bandpass sigma-delta modulation based closed-loop interface with the proposed C/V converter is built. The operation of the C/V converter and the closed loop is analyzed in detail with simulation results in the following sections.

2. C/V converter

For an interface of a certain gyroscope, the C/V converter is a critical block to transfer the signal from the sensor to an electrical signal, i.e., the output voltage of the C/V converter. Considering the conventional CT implementation with a DC detection voltage V_{mid} , a CT current is generated by ΔC when the voltage across the sense capacitance, the nominal capacitance $C \pm \Delta C$, is fixed. This current is integrated by a capacitor C_i to gain an output voltage which acts as an input to the following stages. The inputs of the amplifier within the C/V converter are connected to capacitors, thereby leaving the input CM voltages undefined. Since there is little loop gain around DC in bandpass-based systems, even closed-loop configurations have the same problem. Conventionally, a resistor in parallel with C_i is utilized to provide a DC feedback to settle the input CM voltage by the output CM voltage of the amplifier while negligibly interfering with the AC behavior in the frequency band of interest. It is necessary that the corner frequency set by this resistor is low enough, which requires a huge resistor as the frequency band interested is at low frequencies. Although closed-loop operation eases this requirement relatively, the value of the resistor is normally at the level of $G\Omega$. The reset which is frequently used in switched-capacitor circuits is utilized here to replace the huge feedback resistors while the loop remains in the CT working mode.

The proposed C/V converter is shown in Fig. 1. The clock ϕ whose period is T controls the reset phase and integration phase. The duration of the reset phase in each period is T_{reset} . The duty cycle of ϕ is considerably low, and the frequency of ϕ is a few times higher than that of ΔC . During the reset phase, the input CM voltage V_{cm} of the amplifier within the C/V converter is settled by the output CM voltage. When the reset ends, the C/V converter starts to integrate the current brought by ΔC to generate an output. The output of the C/V converter V_{out} is continuously connected to the following bandpass filter (BPF) during both phases.

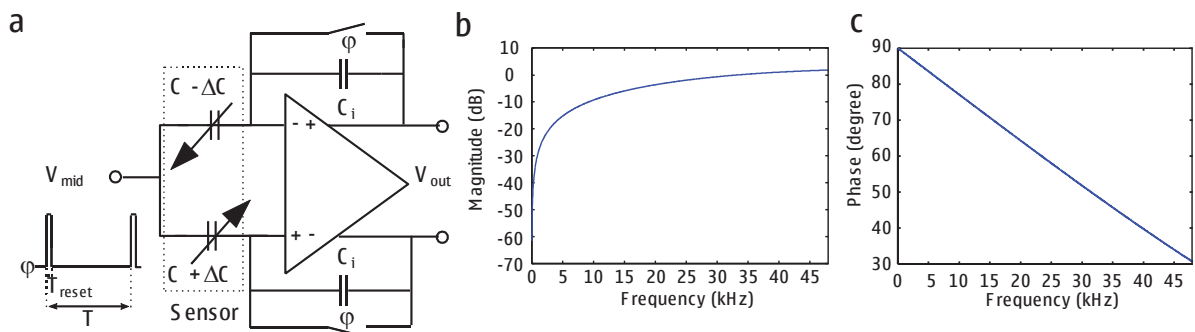


Fig. 1. The proposed C/V converter with reset and frequency response of the C/V converter: (a) schematic of the C/V converter; (b) magnitude response; (c) phase response.

Considering ΔC as input, the output of the C/V converter V_{out} is:

$$V_{out}(t) = K \cdot \left(\sum_{n=-\infty}^{\infty} \Delta C(t) \cdot h(t) - \sum_{n=-\infty}^{\infty} \Delta C(T_{reset} + n \cdot T) \cdot h(t) \right), h(t) = u(t - T_{reset} - n \cdot T) - u(t - (n+1) \cdot T), \quad (1)$$

where $u(t)$ is a unit step function and K is a constant gain equal to $(V_{mid} - V_{cm})/C_i$. As demonstrated by equation (1), V_{out} includes two portions, i.e., tracking with return-to-zero (RZ) format and sample-and-hold (S/H) with RZ format. The harmonics introduced by tracking with RZ are negligible as their magnitudes are significantly low when the duty cycle of clock ϕ is small. ΔC is a modulated signal with narrow bandwidth, normally a few hundreds of Hz. The noise of ΔC at high frequency is considerably suppressed by the sensor. Moreover, the noise is mainly composed of mechanical noise which is not dominant. The noise folding introduced by S/H thus has little impact. Consequently, it is adequate to focus on the response at low frequency. The overall response from DC to $1/2f_{res}$ where f_{res} equal to $1/T$ is:

$$V_{out}(f) = K \cdot (1 - \tau) \cdot (1 - \text{sinc}((1 - \tau) \cdot T \cdot f)) \exp(-j\pi \cdot (1 + 3 \cdot \tau) \cdot T \cdot f) \cdot \Delta C(f), \quad (2)$$

where τ is T_{reset}/T . According to equation (2), the magnitude response without K and phase response of the C/V converter are shown in Fig. 1. Here f_{res} is 96 KHz, the centre frequency of the signal band is 12 KHz and τ is 1/32. As shown in Fig. 1, the magnitude response shows only a little decrease around the signal band. Moreover, an additional phase shift depending on f_{res} and τ is gained which is necessary for the stability of the closed loop.

3. Closed-loop interface

In this work, a CT bandpass sigma-delta modulation based closed-loop interface is implemented with the proposed C/V converter. The diagram of the closed loop is shown in Fig. 2, including the sensor, C/V converter, BPF, quantizer, and force feedback. Generally, compensation is necessary for the stability of the closed loop. A compensator with phase lead is thus employed. In this work, the additional phase shift generated by the C/V converter makes it possible to remove the compensator without interfering with stability. This phase shift is simply adjusted by the duty cycle of the reset clock ϕ , avoiding capacitor or resistor arrays normally used in the CT implementation.

Considering a sigma-delta modulation based closed loop, the quantization noise generates part of ΔC through force feedback. The quantization noise is distributed in the band from $-1/2f_s$ to $1/2f_s$ if the quantized signal is sampled at frequency f_s . The noise folding resulting from the S/H within the C/V converter is thus an issue for the quantization noise. When f_{res} is smaller than the sampling frequency f_s for quantization, the quantization noise is downsampled. Nevertheless, the impact is negligible when f_{res} is equal to or multiple of f_s . In bandpass topologies, f_{res} does not need to be very high since f_s is generally lower than that in lowpass topologies.

4. Simulation results

The natural frequency of the sense mode is 12 kHz, with a quality factor of 1000. The operation is based on mode matching between the sensor's drive mode and the sense mode, which considerably enlarges the sensitivity of the sensor. The sensor and high voltage part are realized in VerilogA. The C/V converter, BPF, and quantizer of the interface are at transistor level using a technology of 0.35 μm . The supply voltage is 3.3 V. The C/V converter consumes a bias current of 40 μA . The BPF is a feedforward Ackerberg-Mossberg biquad, achieving a quality factor around 1000. The bias current of the BPF is 280 μA . The sampling frequency of the quantizer and the reset clock ϕ are both at 96 kHz.

The Bode diagrams of the open loop transfer functions from the normalized input of the sense mode to the output voltage of the BPF are shown in Fig. 3. The phase of the transfer function with reset is within -180° and 180° when the magnitude is high, which ensures the stability of the closed-loop operation. As shown in Fig. 4, the in band noise of the output within a band of 75Hz is -105 dBFS when zero angular rate is applied. The PSD with full scale angular rate at the frequency of DC indicates that the stability of the closed loop with high angular rate is ensured.

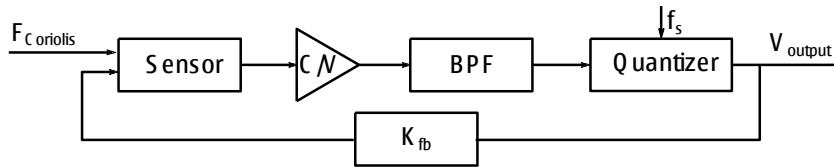


Fig. 2. The diagram of the closed loop

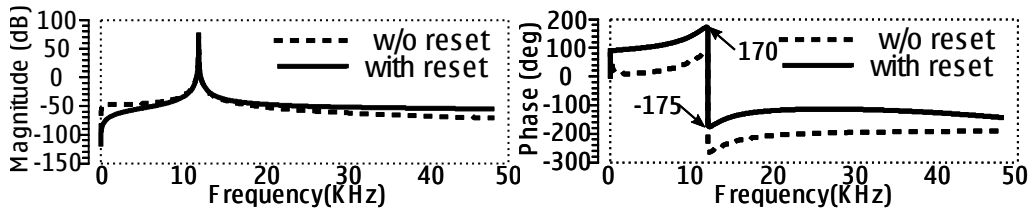


Fig. 3. The Bode diagrams of the open loop transfer functions from the normalized input of the sense mode to the output voltage of the BPF

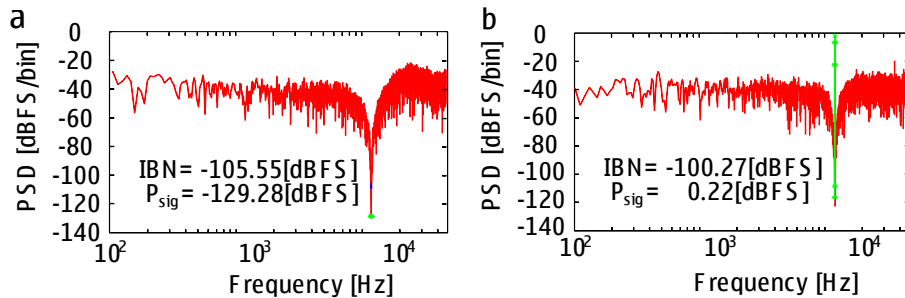


Fig. 4. The simulated PSD of the output of the closed loop: (a) with zero angular rate; (b) with full-scale angular rate as input

5. Conclusions

A CT bandpass sigma-delta modulation based closed-loop interface is implemented with the proposed C/V converter. The C/V converter with reset imposes little impact on CT operation. The compensator can be removed without losing stability. When zero angular rate is applied, the in band noise of the output is at -105 dBFS. The loop remains stable with full scale input, which means the stability with large input is guaranteed. This work provides an approach with a simple implementation decreasing area and power consumption of gyroscope interface circuits.

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